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The influence of the structural steel grade and galvanizing time on the thickness and surface condition of the applied coatings

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ABSTRACT

The study investigated the influence of the structural steel grade and the hot-dip galvanizing process time on the thickness and surface condition of the zinc coating. The S235, S355 and S460 steels were used for the study. The prepared square-shaped test samples with a thickness of 12 mm were immersed in a zinc bath for 90 s and 150 s. The study showed that a longer zinc bath time increased the thickness of the coating layer. The highest susceptibility to the hot-dip galvanizing process was noted for the S235 steel. The coating with the smallest zinc thickness was obtained for the S355 steel, which was most likely due to the percentage of silicon in the material. Additionally, the study analyzed the surface roughness after the coating process. For all the steels tested, an increase in the roughness of the zinc coating was observed in relation to the raw steel material. However, the researchers did not find any correlation between the surface condition and the thickness of the zinc coating. Hardness tests were also carried out, which showed that the galvanizing time and the type of steel substrate affect the hardness of zinc coatings.

Keywords: hot dip galvanizing, application of coatings, coating thickness measurement, roughness measurement.

INTRODUCTION

Galvanizing is a process of producing protective coatings on steel materials. This method is an effective anti-corrosion technique, providing additional properties such as increased mechanical strength and resistance to atmospheric conditions [1-3]. Galvanizing is used worldwide in many industries such as: locksmithing, energy, construction, transport, agriculture and shipbuilding.The wide scope of use of galvanizing technology is associated with a safe, fast and relatively cheap process that allows for the protection of steel materials against the impact of unfavorable external factors [3-5]. During the described technological process, zinc and other additives react with the metallic materials immersed in it, resulting in the formation of a protective coating [3, 6, 7].

There are various methods of galvanizing, however, the two most commonly used are electrolytic galvanizing and hot-dip galvanizing [8]. Each method has a different course and application, and the selection of the appropriate one depends on technical, economic and environmental requirements [8].

Electrolytic galvanizing is a galvanic process in which a surface is covered with a layer of zinc by immersing it in an electrolyte solution containing zinc salts and by the action of an electric current [9]. Under the influence of electric current, zinc ions present in the solution are reduced on the cathode surface, which leads to the precipitation of a zinc layer. Control of process parameters, such as current intensity, electrolyte composition and galvanizing time, is crucial to obtain the desired coating quality [9–11]. Electrolytic galvanizing has many advantages, including the ability to precisely control the thickness of the zinc layer, cover even hard-to-reach areas, and the ability to obtain high-quality surfaces. In addition, the process is economical and environmentally friendly, as it generates less waste compared to other galvanizing methods [9, 11, 12].

Hot-dip galvanizing involves immersing an object in heated, liquid zinc. The process takes place in specially prepared tanks, where the temperature of the molten zinc is about 450 °C [13–15]. Before galvanizing, the surface to be treated with the bath must be properly prepared. If possible, the surface roughness of all elements should not exceed 40 μm. Increased surface roughness accelerates the iron-zinc reaction. Additionally, it contributes to the formation of much larger and thicker zinc coatings [8, 16]. On the outer surface of steel, as a result of the reaction of iron with zinc, intermetallic phases of iron and zinc are formed. The gamma, delta, zeta phases are distinguished, and the last phase of pure zinc is the eta phase. In the formed layers, the iron content decreases towards the surface of the sample. The gamma phase contains from 21 to 28 wt.% Fe, the delta phase from 7 to 11.5 wt.% Fe. The zeta phase contains from 5.8 to 6.7 wt.% Fe, the eta phase contains <0.03 wt.% Fe [17–19]. The structure and properties of galvanic coatings are influenced by, among others, the chemical composition of the zinc bath and the steel substrate, the zinc plating temperature and the immersion time in the bath [3, 17, 20–22]. The chemical composition of steel can affect the growth rate of various zinc layers during the zinc plating process [13, 20–22]. The most important element that influences the structure and thickness of zinc coatings is silicon [13, 14]. In low-silicon steels, in which the silicon content does not exceed 0.03%, the thickness of the zinc coating increases parabolically. Steels containing from 0.12% to 0.22% Si are also characterized by a parabolic increase in coating thickness. On the other hand, steels containing 0.03–0.12% and high-silicon steels (Si content above 0.22%) are characterized by a linear increase in coating thickness. After exceeding 0.03% Si, excessively thick zinc coatings are formed on the surface of the steel sample [13, 23]. Phosphorus is an element that also significantly affects the quality of the resulting coatings [13, 23–25]. Phosphorus content above 0.045% contributes to the formation of rough, thick and brittle zinc coatings. Copper present in steel contributes to the protection of the coating in high humidity conditions. Chromium contained in the chemical composition slows down the oxidation process of steel in warm climates and nickel in cold climates. Additionally, nickel in the galvanizing process reduces the thickness of the coating being created and inhibits the formation of coatings from the Sandelin range. The quality and aesthetics of zinc coatings are also influenced in low concentrations by elements such as bismuth or tin. Tin increases the gloss of the coating and, in combination with bismuth, leads to the formation of visible zinc flowers visible to the eye [15, 23–26].

The engineering and scientific literature describes the galvanizing process in detail, including various techniques and methods used in the industry [15, 27]. Researchers analyze the influence of the types of galvanizing, individual stages and process parameters on the quality of the resulting zinc coatings [15, 28]. Researchers have characterized the corrosion of steel elements, and information is available regarding the effectiveness of galvanizing to prevent it [29, 30]. Scientific research focuses on the impact of the galvanizing process on the natural environment, while more ecological methods of this type of treatment are sought. Economic aspects of galvanizing, investments in galvanizing process infrastructure and economic benefits resulting from extended service life and reduced maintenance are also analyzed [29–31]. Production costs and solutions leading to reduced energy consumption in the galvanizing process are also analyzed.

Sepper S. and his team in [32] analyzed the formation and growth of a zinc coating on steels with different silicon contents (<0.01%; 0.06%; 0.11%; 0.17%; 0.30%). The galvanizing time for the formation of the coating was 4–25 s, and for the growth of the coating 195 s and 1200 s. The researchers concluded, among other things, that the silicon content has no effect on the reactions occurring in the galvanizing process during immersion < 25 s. For immersion times above 25 s, the authors observed a noticeable effect of the silicon content. Moreover, it was noted that silicon affects the hot-dip galvanizing reaction by influencing the diffusion of zinc into the steel and the diffusion of iron into the coating. The higher the diffusion of iron into the coating, the thicker the zinc coating is formed.

Verma N. and his team in the work [33] analyzed the effect of the time of steel immersion in a zinc bath and the effect of nickel addition to the zinc bath and silicon content in steel on the thickness of the zinc coating. The tests were carried out on steel containing silicon in the amount of 0.18% and 28%, the immersion time was 3 min and 5 min, and the nickel content in the bath was 0% and 0.05%. Based on the tests, the authors confirmed that the immersion time has a significant effect on the thickness of the zinc coating formed during the galvanizing process.

Samples immersed for 5 min obtained a thicker coating than samples immersed for 3 min. In addition, the authors proved that with the silicon content in steel at the level of 0.18% and 0.28%, the nickel content in the bath is a more significant factor influencing the thickness of the tin coating than the silicon content in steel. The minimum thickness of the zinc coating was obtained with the immersion time of 3 min and the nickel content in the zinc bath at the level of 0.05%. For steel containing 0.18% Si, a coating of 94 μm thickness was obtained, while for steel containing 0.28% Si, a coating of 100 μm thickness was obtained. By reducing the nickel content to 0% and extending the immersion time to 5 min, the authors obtained a zinc coating thickness of 154 μm for steel containing 0.18% Si and 142 μm for steel containing 0.28% Si. The authors clearly stated that the presence of a nickel alloy in the zinc bath at a level of 0.05% at an immersion time of 3 min limits the formation of an excessively thick zinc coating, which may contribute to lower production costs.

The aim of the study was to analyze the influence of the structural steel type and the duration of the zinc bath on the thickness of the applied coating. Additionally, the influence of the research method on the obtained values of coating thickness was analyzed.

MATERIALS AND METHODS

Materials

The tests were carried out using unalloyed structural steel grades S235, S355 and S460. Square-shaped test samples with dimensions of 100 × 100 mm and thickness of 12 mm were cut from the IPEa 550 steel profile, which is used as a material for ceiling beams, columns, rafters, ground reinforcement elements or vehicle frame elements. In order to be able to immerse the detail in the zinc bath, a technological hole with a diameter of 14 mm was cut. Figure 1 shows the diagram of the test sample 1. The material for testing was selected based on the PN-EN ISO 1461:2023-02 standard, which concerns the selection of material for applying zinc coatings in hot-dip galvanizing technology. Table 1 presents the chemical composition of the individual steel grades.

Hot-dip galvanizing proces

The hot-dip galvanizing process was carried out in industrial conditions. Samples of all types of steel were appropriately prepared before immersion in the zinc bath. The degreasing process began with an alkaline solution containing sodium hydroxide. Then the samples were etched in 15% hydrochloric acid. The next stage was the rinsing process in water. Then the samples were subjected to the fluxing process. The chemical composition of the fluxing bath contained zinc chloride and ammonium chloride. The next stage was the drying process in the drying chamber. The parts were immersed in the zinc bath and then pulled out after 90 s and 150 s. The composition of the zinc alloy complies with the specifications of PN EN ISO 1461. Figure 2 shows the block diagram of the hot-dip galvanizing process.

Analysis of coating thickness

The thickness tests of the applied coatings during hot-dip galvanizing were performed using two measuring devices. The first measuring device used was the Fischer Dualscope MP0

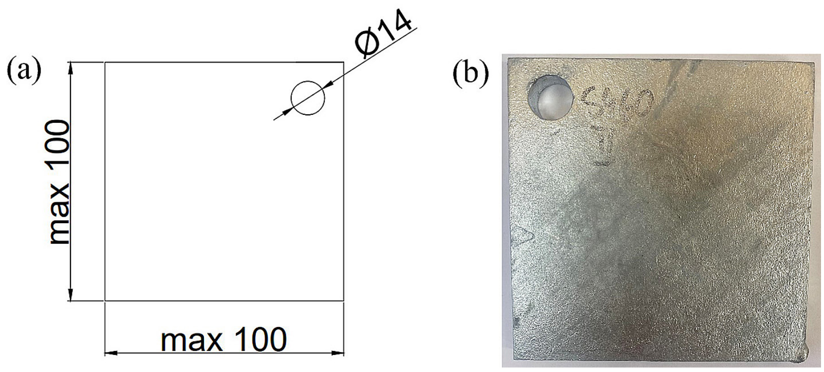

Figure 1. Hot-dip galvanized samples: (a) schematic drawing, (b) research sample

Table 1. Chemical composition of the IPEA 550 profile for individual steel grades

S235						
C	Mn	Si	P	S	Cu	Cr
0.15	0.46	0.19	0.015	0.014	0.02	0.04
Ni	Al	Nb	V	Ti	N	Mo
0.02	0.025	0.002	0.002	0.002	0.005	0.002
S355						
C	Mn	Si	P	S	Cu	Cr
0.08	1.42	0.17	0.018	0.020	0.26	0.09
Ni	Al	Nb	V	Ti	N	Mo
0.12	0.017	0.039	0.008	0.021	0.009	0.03
S460						
C	Mn	Si	P	S	Cu	Cr
0.15	1.41	0.19	0.015	0.009	0.16	0.08
Ni	Al	Nb	V	Ti	N	Mo
0.10	0.015	0.027	0.06	0.001	0.006	0.002

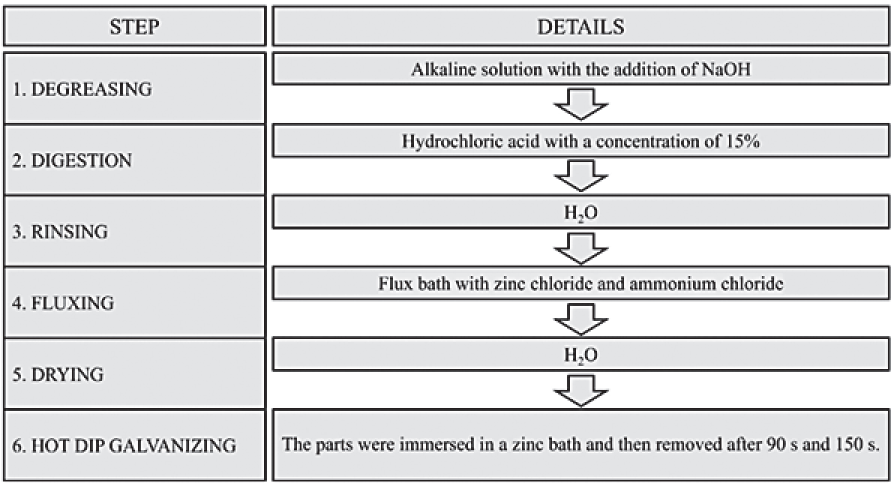

Figure 2. Block diagram of the hot-dip galvanizing proces

(USA, Windsor). In the case of testing zinc coatings, the measuring device uses the magnetic induction method. The purpose of using another meter for testing was to exclude measurement error when using only one testing device. The second tool used was the Defelsko Positector 6000 (USA, Ogdensburg), which was equipped with an angular FNRS measuring probe. Similarly to the previous device, the magnetic induction method was used to measure the coating thickness. Measurements with both devices were performed in accordance with the PN-EN ISO 2178:2016-06 standard (Non-magnetic coatings on magnetic substrates – Coating thickness measurement – Magnetic method). Each of the devices used was appropriately calibrated before the measurement using reference blocks supplied by the manufacturer. On the test sample, 20 measurement points were randomly selected and then the measurement was taken. Based on the received device readings, the average value of the zinc coating was calculated along with the standard deviation.

Optical microscopy

Digital microscopic photographs were taken to provide additional confirmation of the results obtained from the magnetic meter readings and to visualize the applied zinc coatings. Analysis of the structure and thickness of the zinc coatings was measured based on photographs of appropriately prepared metallographic sections of the research samples. The photographs were taken using a high-resolution Keyence VHX-7000 digital optical microscope equipped with a VH-Z100R lens (Osaka, Japan).

Surface roughness measurements

The roughness measurements were performed using the contact method using the MarSurf GD 120 device (Mahr GmbH, Göttingen, Germany), equipped with the MFW-250 measuring head. Each measurement was performed using a measuring needle with a radius of 2 μm. During the linear 2D roughness measurement, 20 measurements were performed at randomly selected locations, from which the mean value with standard deviations was calculated. During the preliminary tests, the length of the elementary section λc was determined, which was 2.5 mm for all the analyzed test samples. The entire measuring section ln was 15 mm.

Hardness of coatings

The hardness of zinc coatings was measured using two methods. The first one was surface hardness determined by the Brinell method (HBW). Then, microhardness was tested using the Vickers method (HV) on previously prepared metallographic sections. Brinell hardness testing was performed using the Struers Duramin-500 device (Copenhagen, Denmark). The test load was 1839.38N, the diameter of the indenter ball was 2.5 mm, and the loading time was 10 seconds. The measurements were carried out in accordance with the PN-EN ISO 6506 standard. A series of tests were performed both on samples containing a zinc coating and on raw steel. Ten measurements were made on each of the analyzed samples, from which the mean and standard deviation were determined.

Vickers microhardness testing was performed using a Shimadzu HMV-G20 microhardness tester (Kyoto, Japan). The test load was 490.4 mN (HV 0.05), and the loading time was 10 s. The test was carried out in accordance with the PN-EN ISO 6507 standard. The adopted research methodology included measurement at a distance of 10 μm from the zinc-steel boundary, regardless of the type of steel and the galvanizing time. Five measurements were made in each measurement series, on the basis of which the mean and standard deviation were calculated. An example microscopic photo showing the measurement principle is shown in Figure 3.

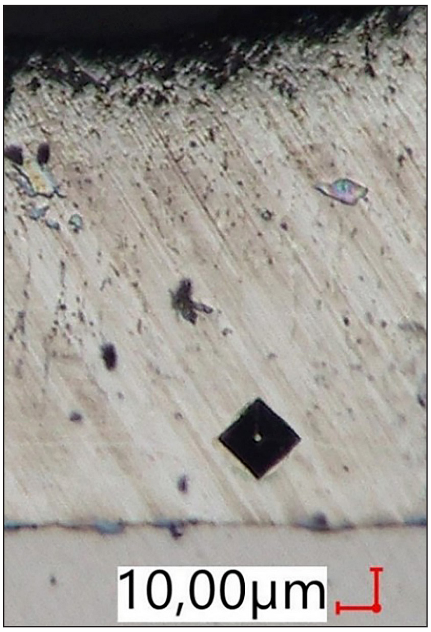

Figure 3. Methodology for measuring the microhardness of zinc coatings

RESULTS

Thickness of zinc coating

Among all types of structural steel, the highest zinc coating thickness was obtained for S235 steel for both 90 s and 150 s galvanizing times. Immersion of S235 steel for 150 seconds resulted in a thickness of 138.57 μm, which is approximately 111% greater than that of S355 steel (65.69 μm) and approximately 40% greater than that of S460 steel (99.42 μm). During immersion of the samples for 90 seconds, similar results were obtained. The thickest protective coating was obtained for S235 steel (91.28 μm), then for S460 steel (71.49 μm) and for S460 steel (55.88 μm). These values were lower by 39% (S355 steel) and 22% (S460 steel) respectively in relation to S235 steel. The test carried out that the immersion time of the test samples significantly affects the coating thickness. For each of the analyzed structural steels, the zinc bath time of 150 s resulted in a thicker protective coating. The greatest differences between measurements taken at different times were obtained for S235 steel, where the bath time of 90 seconds (91.28 μm) resulted in a coating approximately 34% smaller than that obtained in 150 s (138.57 μm).

The smallest difference was noted for S355 steel, where the difference between measurements taken after 90 s (55.88 μm) and 150 s (65.69) was only 15%. For S460 steel the difference was 29%.

Based on the obtained results, it can be concluded that S235 steel is the most susceptible to the hot-dip galvanizing process. The least susceptible to the process is S355 steel. A graphical representation of all coating thickness measurements is shown in Figure 4.

The above results were presented based on the readings of the Fischer Dualscope MP0 meter. Figure 4 shows the results obtained using the Defelsko Positector 6000 device. The results obtained with the latter device are very similar to those on the basis of which the previous results were described. Based on the obtained results, it can be concluded that S235 steel is the most susceptible to the hot-dip galvanizing process. The least susceptible to the process is S355 steel. A graphical representation of all coating thickness measurements is shown in Figure 5.

Surface roughness

Analyzing the results of the surface condition of the research samples after the hot-dip galvanizing process, it can be observed that the highest roughness was characterized by the sample made of S235 steel immersed in a zinc bath for 90 seconds. The surface before galvanizing was characterized by a Ra parameter of 4.22 µm, while after galvanizing this value was 9.25 µm, which gives an increase of about 120%. The galvanizing process in 150 seconds was characterized by a lower roughness value of 8.47 µm, which gives an increase of 101% in relation to the initial value (Fig. 6).

A similar relationship was obtained for the remaining test samples. Samples galvanized for 90 seconds were characterized by a higher average roughness than those galvanized for 150 seconds. These differences are, however, small and based on standard deviations, this relationship cannot be unequivocally confirmed. The lowest roughness was recorded for S355 structural steel, where the obtained increase in the Ra parameter was 38% for a galvanizing time of 90 seconds and 34% for a coating time of 150 seconds. S460 steel showed similar results to those observed for S355 steel. The

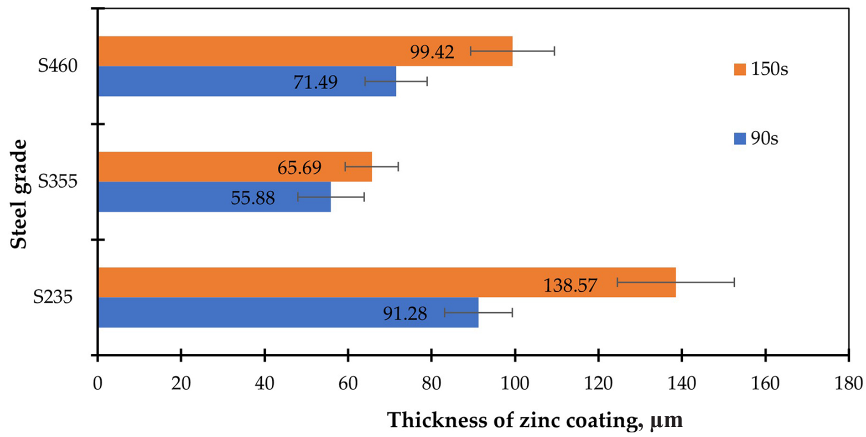

Figure 4. Thickness of zinc coating measured with Fischer Dualscope MP0

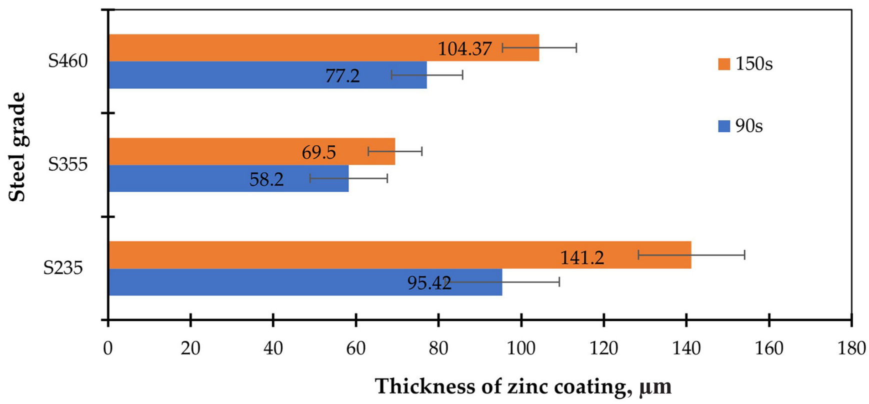

Figure 5. Thickness of zinc coating measured with Defelsko Positector 6000

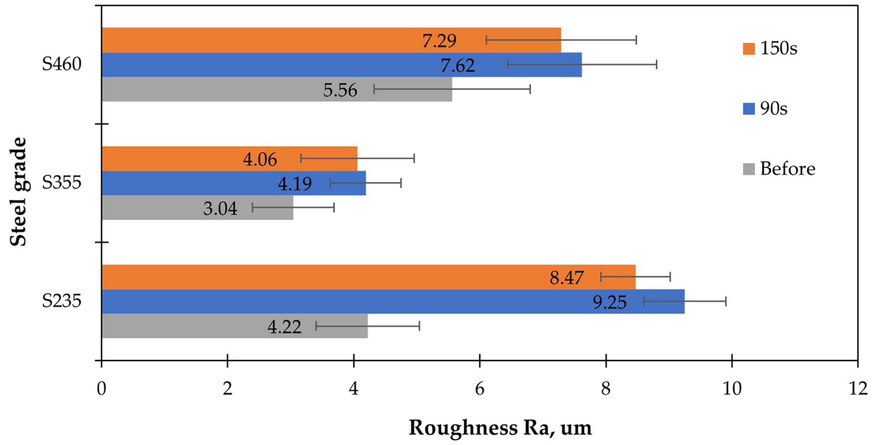

Figure 6. Surface roughness of analyzed steels

increase in roughness during the zinc bath for 90 and 150 seconds was 37% and 31%, respectively. A comparative summary of the Ra parameter and the coating thickness is presented in Table 2.

A comparison of surface condition results and coating thickness revealed no correlation between these parameters. The highest zinc coating thickness obtained for S235 – 90s steel (138.57 μm) was characterized by a roughness of 8.47 μm, while the galvanizing time of 90 seconds resulted in a coating of almost 50 μm thinner. However, the surface roughness for the described example was higher than that obtained for 150 seconds and amounted to 9.25 μm. In the case of galvanizing steel S460 for 150 seconds, the obtained roughness was 7.29 μm and was similar to that obtained for steel S235 for the same galvanizing time, despite the fact that in this case the coating thickness also differs significantly and amounts to 99.42 μm and 138.57 μm, respectively. Table 3 shows the change in surface roughness as a result of applying the zinc coating.

Figure 7 shows sample digital images showing the surface condition of the tested samples for S235 steel before the galvanizing process (a) and after the galvanizing process lasting 90 s (b).

Additionally, Figure 8 shows sample photographs of the zinc coatings applied. These photos illustrate the homogeneity and continuity of the zinc coatings, which is crucial for assessing the quality of anti-corrosion protection. Additionally, visual analysis confirms the consistency of the

Table 2. Comparison of the thickness of the obtained coating with the surface roughness

Steel grade	Galvanizing time [s]	Roughness [μm]	Thickness of zinc coating [μm]
S460	150	7.29	99.42
	90	7.62	71.49
S355	150	4.06	65.69
	90	4.19	55.88
S235	150	8.47	138.57
	90	9.25	91.28

Table 3. Comparison of the surface roughness of steel before and after galvanizing

Steel grade	Galvanizing time [s]	Roughness of raw steel [μm]	Roughness of the zinc coating [μm]	Increase in roughness [%]
S460	150	5.56	7.29	31.12
	90		7.62	37.05
S355	150	3.04	4.06	33.55
	90		4.19	37.83
S235	150	4.22	8.47	100.71
	90		9.25	119.19

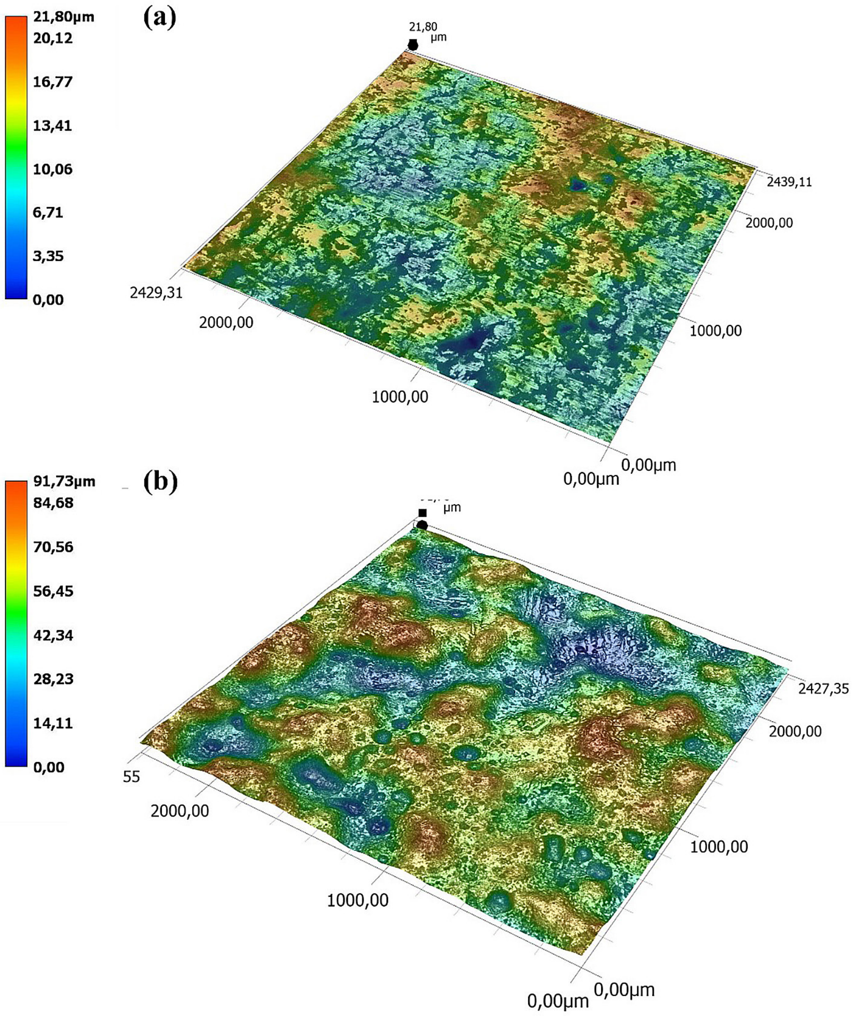

Figure 7. Surface condition of the test samples before hot-dip galvanizing (a) and after galvanizing for 90 s (b)

coating thickness with the values measured using magnetic meters, indicating the correctness of the measurements performed and their compliance with the actual results. The presented photographs complement the quantitative results and provide additional evidence confirming the reliability of the research methods used in the work.

The influence of the chemical composition of steel on the thickness of the zinc coating

The growth of the zinc coating in the hot-dip galvanizing process is influenced mainly by silicon, followed by other elements such as carbon, manganese, sulfur, and phosphorus [13, 14, 34–36].

The S235 and S460 steels used have the same silicon content of 0.19%, while the S355 steel contains 0.17% silicon. All the tested steel grades fall within the general range of silicon content (from 0.14% to 0.25%) for steel recommended for the hot-dip galvanizing process. Then, such steels should obtain a satisfactory thickness and quality of the zinc coating in relation to steels with low silicon content and high silicon content [34, 37]. Such coatings are characterized by a shiny surface, and their thickness increases with increasing silicon content [37]. S355 steel resulted in the thinnest zinc coating, likely due to its lower silicon content.

Another difference in the chemical composition of the tested steels is the carbon content. For S235 and S460 steels, the percentage of carbon content is 0.15%, while for S355 steel the carbon content is 0.08%. According to the literature for low-carbon steels, the zinc layer on the steel surface may develop. However, for steels with a carbon content of up to 0.2%, the carbon content has not been shown to have a significant effect on the formation and thickness of the zinc coating. Only above 0.3%C can a disproportionate increase in the zeta's thickness phase in the zinc coating be observed [33, 34, 38]. For the obtained results,

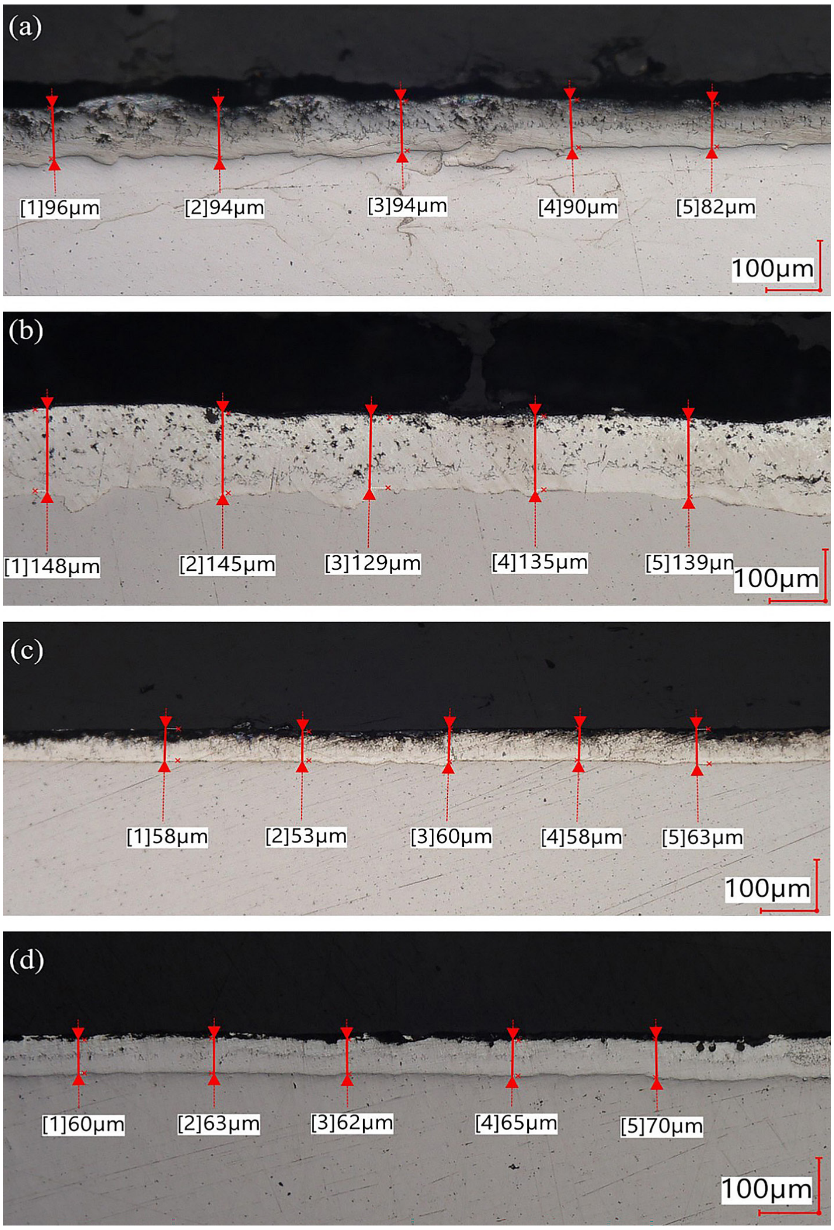

Figure 8. Thickness of zinc coatings on analyzed steels: (a) S235 90s, (b) S235 150s, (c) S355 90s, (d) S355 150s

the carbon content in the steel probably did not affect the thickness of the zinc coating.

S355 and S460 steels have similar manganese content in their chemical composition at the level of 1.41% Mn. However, S235 steel has only 0.46% Mn in its composition. According to the literature, the presence of manganese in the chemical composition of steel subjected to hot-dip galvanizing is not analyzed in relation to the effect on the thickness and composition of the zinc coating [34]. Therefore, differences in the amount of manganese in the chemical composition of the tested steels may also not affect the thickness of the zinc coating.

Another chemical element with different content in the tested steels is sulfur. Research in [34] demonstrated that only sulfur levels above 0.15% can influence the thickness of the zinc coating. In the tested steels the sulfur content is much lower, therefore this element could not affect the thickness of the zinc coating either.

Hardness of coatings

Table 4 shows the results of surface hardness measurements obtained by the Brinell method (HBW) before and after the hot-dip galvanizing process. For each of the analyzed steels, there is a noticeable decrease in the surface hardness of the material under the influence of hot-dip galvanizing, regardless of the galvanizing time used.

Tabela 4. Measurement of surface hardness of zinc coatings using the Brinell HBW method

Type of steel	Galvanizing time [s]	Hardness of the base material [HBW]	Surface hardness after galvanizing [HBW]	Percentage decrease in hardness [%]
S235	90	123.51 ± 1.38	119.17 ± 7.05	3.52
	150		116.18 ± 2.48	5.95
S355	90	167.67 ± 1.21	143.67 ± 4.27	14.32
	150		139.50 ± 3.94	16.80
S460	90	192.01 ± 2.31	172.33 ± 8.43	10.25
	150		156.17 ± 3.97	18.67

However, a longer zinc bath time (150 s) results in a greater decrease in surface hardness compared to a shorter galvanizing time (90 s). Zinc is a relatively soft metal, so its main function in a protective coating is not to increase mechanical strength, but to protect against corrosion. The increase in the thickness of the zinc coating resulted in less resistance during the penetration of the measuring tool during the Brinell hardness test, as a result of which the obtained surface hardness is lower. S235 steel, which has the lowest initial hardness, showed the smallest change in hardness after galvanizing. At a galvanizing time of 90 seconds the difference is 3.52%, while at 150 seconds an increase to 5.95% was observed. In the case of S355 and S460 steels, the decrease in surface hardness is more pronounced. For S355 the difference is 14.32% (90 s) and 16.80% (150 s), while for S460 it is 10.25% (90 s) and 18.67% (150 s).

Hakim A.A. and his team in [39] examined the surface hardness of the zinc coating on low-carbon steel at various times during the galvanizing process. The authors also observed a decrease in the surface hardness value of the tested coatings in relation to the base material with the extension of the galvanizing time. Researchers indicated that the described decrease is due to the thicker zinc layer that is formed with the extension of the galvanizing time. Other literature data [15, 17, 40] also indicate that zinc coatings produced during the hot-dip galvanizing process are characterized by lower surface hardness compared to the base material. Additionally, the presented research proves that steels with increased strength (S355, S460) are more susceptible to changes in hardness in the hot-dip galvanizing process, as a result of which they may lose their mechanical properties. The literature also indicates that the change in hardness may depend on the chemical composition of the steel - the presence of elements such as silicon (Si) or manganese (Mn) may affect the intensity of zinc diffusion and the degree of changes in mechanical properties [32, 34].

Based on the results presented in Table 5, it can be said that the microhardness of zinc coatings increases with the extension of the hot-dip galvanizing time. The HV values obtained for each of the analyzed steels indicate the impact of galvanizing time on the mechanical properties of the zinc coating. After 90 seconds of galvanizing, the highest microhardness of the coating was recorded for S235 steel (271.2 HV), and the lowest for S460 (241.3 HV). After extending the time to 150 seconds, there was an increase in microhardness for all tested materials, with the highest increase recorded for S460 steel (34.14%), and the smallest for S235 steel (15.67%). It is worth noting that the obtained results of Vickers microhardness measurements were obtained with the assumptions presented in the methodological part of the article, i.e. 10 μm from the steel-zinc boundary. In order to precisely analyze the microhardness of zinc coatings, it would be necessary to perform measurements in individual phases of the zinc coating (η, ζ, δ, Γ). The time of the hot-dip galvanizing process is not the only

Tabela 5. Measurement of microhardness of zinc coatings using the Vickers HV method

Type of steel	Galvanizing time		Percentage increase [%]
	90 s	150 s	
S235	271.2 ± 26.50	313.7 ± 43.9	15.67
S355	266.7 ± 19.4	329.0 ± 41.15	23.35
S460	241.3 ± 12.66	323.7 ± 22.6	34.14

parameter that may affect the microhardness of zinc coatings. It is advisable to carry out further, more detailed research to explain changes in the microhardness of the tested zinc coatings.

As part of the experiment, the hot-dip galvanizing process of the tested steels was carried out in industrial conditions. Under these conditions, a number of different external factors may affect the thickness and structure of the resulting zinc coatings, and thus their mechanical and functional properties in relation to the galvanizing process in laboratory conditions. Scientific research has begun to appear in the literature, reflecting the influence of external factors that may occur in industrial production on the formation of zinc coatings. These studies indicate that external factors, such as e.g. contamination on steel, may significantly influence the formation of zinc coatings [3].

CONCLUSIONS

The conducted tests have shown that a longer immersion time of the samples in the zinc bath contributes to getting zinc coatings of greater thickness. For all tested structural steels, samples immersed for 150 s obtained a thicker zinc coating than samples kept in the bath for 90 s. Increasing the immersion time of the samples from 90 s to 150 s for S235 steel contributed to an increase in the coating thickness by 34%. For S460 steel, this increase was at a similar level and amounted to 29%. However, the smallest increase in the zinc coating thickness associated with a longer immersion time of the samples occurred for S355 steel, with an increase of only 15%.

Tests of the zinc coating roughness showed an increase in the Ra parameter for the surface of all tested structural steel grades compared to the roughness of the raw material surface. The roughness of S235 steel increased the most, reaching a level of 120%. The research found no correlation between the surface condition and the thickness of the zinc coating. All analyzed structural steels obtained a higher Ra parameter for coatings that were formed during galvanizing for up to 90 s. In the course of further research, it would be reasonable to examine the effect of the type of steel on the roughness of the surface of previously prepared raw samples with the same value as tribological parameters.

Among all the tested steels, the lowest thickness of the zinc coating was got by the S355 steel. This steel has the lowest silicon content in its chemical composition of all the tested steels. Small differences in the amount of chemical elements that can affect the formation of the zinc coating allow for an unambiguous determination of the influence of individual elements on the thickness of the zinc coating of the tested steels.

Various factors can ultimately affect zinc coating formation, influencing the industrial conditions under which hot-dip galvanizing of the tested structural steels S235, S355, and S460 was carried out. These factors include, among others, contamination of the zinc bath, control of the immersion time, and the surface condition of the details.

Hardness measurements carried out using the Brinell (HBW) and Vickers (HV) methods showed that both the galvanizing time and the type of steel substrate may have a significant impact on the mechanical properties of zinc coatings. The analysis of the results obtained using the Brinell method indicates that the surface hardness of the zinc coating is close to or slightly lower than the hardness of the base material for all types of tested steel. Microhardness measurements using the Vickers method showed that the zinc coating after a longer galvanizing time is characterized by higher microhardness.

The formation of a zinc layer on a steel substrate depends not only on the chemical composition of the steel substrate but also on the galvanizing process parameters. Finding a correlation between these factors allows for the production of coatings of appropriate quality and thickness.

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